Preprint typeset in JHEP style. - PAPER VERSION

hep-th/9906126
RU-99-22

Remarks on M Theoretic Cosmology

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Abstract: I present cosmological arguments which point towards a Horava-Witten like picture of the universe, with the unification scale of order the fundamental gravitational scale. The SUSY breaking scale is determined by the dynamics of gauge fields which are weakly coupled at the fundamental scale. Bulk moduli whose potential originates at short distances are the inflatons, while bulk moduli whose potential originates from SUSY breaking are the origin of the energy density in the present era. The latter decay just before nucleosynthesis, and a consistent theory of baryogenesis requires that there be renormalizable baryon number violating interactions at the TeV scale. The dark matter is a boundary modulus, perhaps the QCD axion, and the temperature of matter radiation equality is related to the ratio between the fundamental and effective four dimensional Planck scales. The same ratio determines the amplitude of fluctuations in the microwave background.

Keywords: String Duality, Cosmology.

Contents

The purpose of this note is to revisit certain issues in string (now M theory) cosmology, in light of the string duality revolution. Our previous investigations of these issues are contained in [2][5]. Our basic claim is that certain observations in cosmology suggest (though we will certainly not claim that they prove) that the world is close to a vacuum state of M-theory similar to that which arises from Calabi Yau compactification of the strongly coupled heterotic string of Horava and Witten [22]. We will describe what may be a large class of generalizations of the Horava Witten scenario.

The major issues we discuss may be itemized as follows:

- One of the central claims of [2] , following the seminal work of [1] , was that moduli of string theory are natural inflaton candidates. However, there is a sort of contradiction in this statement. Moduli are cleanly defined only when they are true zero modes. Inflatons must have a potential. In [2] this contradiction was hidden beneath the assumption that the natural scale of the potential during inflation is much smaller than the fundamental scale of string theory, which was identified with the four dimensional Planck mass. However these papers also made much of the coincidence between the scale of inflationary vacuum energy and the Unification scale. Witten's explanation of the ratio between the Unification and Planck scales in the context of the Horava-Witten scenario[23], identifies the former with the fundamental scale of the theory. In this context, the separation of inflaton fields with a potential of order the fundamental scale of M theory from the rest of the high energy degrees of freedom of the theory seems highly suspicious. We will see that these conundra are simultaneously resolved in any scenario with 8 supercharges (SUSYs) preserved in the bulk and only 4 preserved on certain lower dimensional submanifolds or branes. We will argue that there may be many such compactifications of M theory, generalizing that of Horava and Witten. In such compactifications, N_e e-foldings of inflation require only a small coefficient of order $1/N_e$ in the superpotential of bulk moduli. The size of primordial energy density fluctuations is naturally explained in terms of the unification scale and the four dimensional Planck scale.

- In [2] the existence of an independent, lower, scale for SUSY breaking was considered an embarrassment. Here we ascribe it to the existence of a true moduli space of the low energy effective theory with 4 SUSYs, which is identified as the locus of an enhanced discrete R symmetry with certain properties. Nonperturbative low energy gauge interactions spontaneously break both this R symmetry and the remaining four supercharges. The details of the resulting physics depend somewhat on whether we assume the true moduli space contains bulk moduli, or only fields whose origin is on one of the branes. We somewhat prefer the case with bulk moduli because it leads to a natural explanation of the relation between the scales of R symmetry and SUSY breaking, that is necessary in any supergravity theory in which the cosmological constant vanishes. In passing we note that this scenario for SUSY breaking resolves the overshoot problem of [10].

- Both bulk and brane modes of SUSY breaking lead to a version of the cosmological moduli problem [7]. We review a resolution of this problem [5] in which the moduli decay and reheat the universe to a temperature just above that needed for nucleosynthesis. The baryon asymmetry is produced in the decay of the moduli. This implies that the low energy theory at energies of order 1 TeV contains renormalizable baryon number violating interactions . As a consequence, there is no natural SUSY candidate for dark matter.

- We review and generalize the observation of [5] that a brane modulus with sufficiently small potential is a natural dark matter candidate in the above scenario. The QCD axion (with a decay constant of order the unification scale) is a possible realization of this mechanism. However, there is nothing which requires the potential of the dark matter candidate to be of the QCD scale.

1. Moduli and Inflation

Generic compactifications of M theory to four dimensions with only four SUSYs have no moduli. That is, there are no theorems which prevent the occurence of a superpotential on the would be moduli space. Furthermore, all symmetries of M theory are gauge symmetries. As a consequence of D-terms, the true moduli space is made up of fields invariant under all continuous gauge symmetries. Thus, the superpotential is restricted only by discrete symmetries and these generically do not require it to vanish. The exception is a discrete complex R symmetry, [8]. The submanifold of field space invariant under such a symmetry, and containing no directions of R charge 2, is a true moduli space[1].

[1]Another possible region of field space where the superpotential vanishes has been explored by Witten [9]. Witten's argument for vanishing superpotential uses a $U(1)$ symmetry valid only in a certain large

Most discussions of the phenomenology of string/M theory have been based either on low energy SUGRA, or weakly coupled string expansions. In these discussions the apparent moduli space of the theory is much larger than the true moduli space. There are theorems which prevent the occurence of a superpotential to all orders in the perturbative expansion. If one works in the regime where nonperturbative corrections to the superpotential are small then the phrase "superpotential for moduli "is not an oxymoron. It was in this context that the idea of moduli as inflatons was proposed [1][2] . A serious problem with this regime was pointed out long ago by Dine and Seiberg [11]. Within the context of a systematic perturbative expansion one cannot stabilize the moduli (small couplings or large radii) whose large values justify the expansion. Racetrack models [18] and Kahler stabilization [4] are two attempts to get around this problem. Neither leads to a reliable calculational framework, and their fundamental postulates have not been verified.

Another reason for avoiding extreme regions of moduli space was pointed out by Moore and Horne [19]. In extreme regions of moduli space, the metric on the space can be reliably calculated and the infinite regions have finite volume. This means that the system dynamically avoids the extreme regions. For example, if the potential has two minima with vanishing cosmological constant, one in the interior of moduli space and the other in one of the extreme regions, then a generic motion of the system will end up at the minimum in the interior.

In a vacuum state with no large moduli on the other hand, it is not clear what the term modular inflation could mean. This is particularly true if one adopts Witten's explanation of the ratio between the Planck and unification scales, with the concomitant conclusion that the fundamental scale of M theory is on the order of 10^{16} GeV. The simplest interpretation of the magnitude of primordial energy density fluctuations in inflationary cosmology invokes a vacuum energy during inflation of approximately this order of magnitude. In what sense can fields with a potential energy of this order of magnitude be considered moduli? Recall that the motivation for separating moduli out from the other degrees of freedom of M theory is that they are supposed to parametrize low energy motions of the system among would be ground states.

In fact, scenarios like that of Horava and Witten contain the clue to an answer to this question. The universe is separated into "branes "and bulk, and the latter has more SUSY than the former. Thus, the bulk universe has 8 approximately conserved supercharges and thus contains fields which would act as true moduli if it were not for the presence of the branes. The superpotential for the moduli is generated on the branes.

Let us examine the consequences of this fact. At an energy scale small compared to the mass of the bulk Kaluza-Klein modes on the compact manifold, the world is effectively

volume limit to draw exact conclusions about the superpotential. I find it mildly suspicious and will not include Witten's region in the discussion here, but it may have an important role to play.

four dimensional. The moduli become fields in this four dimensional effective field theory. Since the effective theory has only four SUSYs, these fields have a superpotential. Since it comes only from the vicinity of the branes on which the larger SUSY algebra is broken, it is independent of the volume of the internal space, and has, by dimensional analysis, the form

$$W = M^3 w(\theta_a) \tag{1.1}$$

where θ_a are dimensionless parameters characterizing the internal geometry. On the other hand, the kinetic term for these zero modes, just like the Einstein term for the zero modes of the gravitational field, is proportional to the volume V_7 of the internal manifold, and has the form

$$M^9 V_7 \sqrt{-g} G_{ab}(\theta) \nabla\theta_a \nabla\theta_b. \tag{1.2}$$

Note that $M^9 V_7 = m_P^2 = \frac{1}{8\pi G_N}$ is, as the notation indicates, the same coefficient which multiplies the Einstein action. Furthermore, although the volume V_7 is itself a modulus, when we pass to the Einstein conformal frame in which V_7 is replaced by its vacuum value, the kinetic term of the moduli is rescaled in precisely the same manner as the gravitational action. It is then natural to define canonical scalar fields by $\phi_a = m_P \theta_a$. Their action has the form

$$\int \sqrt{-g} G_{ab}(\phi/m_P) \nabla\phi^a \nabla\phi^b - \frac{M^6}{m_P^2} v(\phi/m_P). \tag{1.3}$$

The slow roll equations of motion derived from this action are

$$3H d\phi^a/dt = -\frac{M^6}{m_P^2} G^{ab} \frac{\partial v}{\partial \phi^b}. \tag{1.4}$$

and lead to the equation

$$dv/dt = \frac{M^3}{3m_P^2 \sqrt{v}} \partial_a v G^{ab} \partial_b v. \tag{1.5}$$

where ∂_a refers to the derivative with respect to the dimensionless variable θ^a. We have also used the slow roll expression for H in terms of the potential. From 1.5 we immediately derive an expression for the number of e-foldings

$$N_e = 3 \int \frac{v}{\partial_a v G^{ab} \partial_b v} \partial_c v d\theta^c. \tag{1.6}$$

where the integral is over the trajectory in moduli space that the system follows during the time interval when the slow roll approximation is valid. We see that in order to obtain a large number of e-foldings we need a potential which is flat in the sense that $|\partial v|/v \sim 1/N_e$. The phenomenologically necessary $N_e \sim 60$ can be achieved with only a mild fine tuning of dimensionless coefficients. Correspondingly, the conditions on the potential which ensure the validity of the slow roll approximation are order one conditions on the derivatives of the potential and do not contain any small dimensionless numbers.

The fact that actions of the form 1.3 give rise to inflation with minimal fine tuning, and that such actions naturally arise for moduli in string theory was pointed out in [2]. The general point that moduli might provide the flat potentialled, weakly coupled fields necessary to inflation was first made in [1]. Here we note that in brane scenarios, it is the *bulk moduli* which play this role. By contrast, moduli associated with a single brane will have a natural scale M and do not play the role of inflatons in quite as gracious a manner.

Another pleasant surprise awaits us when we plug the potential from 1.3 into the standard formula for the amplitude of the primordial energy density fluctuations generated by inflation. Up to numbers of order one we find

$$\frac{\delta\rho}{\rho} \sim N_\lambda (M/m_P)^3 \sim 10^{-5} \tag{1.7}$$

where the numerical value comes from the measured cosmic microwave background fluctuations, and $N_\lambda \sim 50$. This gives $M \sim (2/10)^{1/3} \times 2 \times 10^{16}$ GeV, which, given the crudeness of the calculation, is the unification scale. To put this in the most dramatic manner possible, we can say that a brane scenario of the Horava-Witten type, given the unification scale as input, *predicts the correct amplitude for inflationary density fluctuations*. Furthermore, the whole scenario only makes sense because of the same large volume factor that underlies Witten's explanation of the ratio between the Planck and unification scales. This is necessary at a conceptual level to understand why it is sensible to think about a modulus with a super potential of order the fundamental scale, and at a phenomenological level to understand the magnitude of the density fluctuations.

Although it has no connection with our discussion here we cannot resist pointing out the other piece of evidence for a scale of the same order as M. Any theory of the type we are discussing would be expected to contain corrections to the standard model Lagrangian of the form (in superfield notation) $\frac{1}{M}LLH^2$, which gives rise to neutrino masses. It is a matter of public record [14] now that such masses exist, with an estimated value for M between .6 and 1.8×10^{15} GeV. Although this is an order of magnitude shy of the unification scale I believe the uncertainties in coefficients of order one in dimensional analysis could easily make up the difference. If not, we will have the interesting problem of explaining the existence of two close but not identical energy scales in fundamental physics. [17].

Finally, we want to note that this scenario for inflation does not suffer from the runaway problem pointed out by Brustein and Steinhardt [10]. These authors noted that the inflationary vacuum energy is much larger than the SUSY breaking scale. Furthermore, the minimum of the effective potential was assumed close to the region of weak string coupling. There was then a distinct possibility that the inflaton field would overshoot the small barrier separating it from the extreme weak coupling regime where string theory is incompatible with experiment. In the present scenario, the coupling is not assumed to be weak (nor the volume extremely large). Furthermore the inflationary potential has nothing to do with SUSY breaking. There is no runaway problem at all.

1.1. SUSY breaking

The authors of the papers in [2] agonized over the discrepancy between the unification scale and the scale of SUSY breaking. In fact, they discussed and discarded what I now believe is the obvious solution of this problem, because of problems specific to weakly coupled string theory. The obvious way to avoid SUSY breaking at the scale M, is to insist that the superpotential 1.1 has a SUSY minimum. In fact, the existence of such minima is generic , requiring only the solution of n complex equations for n unknowns. However, in general, the superpotential will not vanish at such a minimum but instead will give rise to a negative cosmological constant. We refer the reader to [2] for the elementary argument that in a postinflationary universe, such a SUSY point in moduli space is not a stable attractor of cosmological solutions. Instead, generic solutions which try to fall into such a minimum, recollapse on microscopic time scales.

The stable postinflationary attractors of a supersymmetric cosmology are points in moduli space with vanishing superpotential and SUSY order parameters. These can be characterized in terms of a symmetry. Namely, any complex R symmetry forces the superpotential to vanish, and if there are no fields of R charge 2 then the SUSY order parameter vanishes as well. The R symmetry must of course be discrete, since we are discussing M theory. If in addition, there do exist fields of R charge 0, then there will be an entire submanifold on which the superpotential vanishes and SUSY is preserved. Our future considerations will concentrate on this submanifold, which, following the terminology in the introduction, we call the true moduli space. It is the locus of restoration of a discrete R symmetry with the above properties.

Before proceeding to the discussion of SUSY breaking on the true moduli space, we should introduce the final characters in our story, the boundary or brane moduli. We could in fact have inserted such fields, which arise as excitations localized on one of the branes, into our discussion of inflation. However, they would have been of little use there, as their natural scale is M rather than m_P and they are rapidly driven to their instantaneous minima during the inflationary era. At lower energies however they will play an interesting role.

In addition to these moduli fields, any brane scenario will contain a variety of gauge fields and matter fields in nontrivial representations of the gauge group. The moduli will interact with these fields via the moduli dependence of bare gauge and yukawa coupling parameters in the effective theory as well as thru a variety of irrelevant operators. If the gauge couplings are asymptotically free and do not run to infrared fixed points at low energy, this description of the physics only makes sense if the bare gauge couplings are sufficiently small that the scale at which the effective coupling becomes large is substantially below the scale M. Otherwise it is not consistent to include the gauge degrees of freedom in the low energy effective theory. The weakness of bare couplings in these scenarios is not evident a priori, as it would be in a purely perturbative approach. The underlying physics is assumed to be strongly coupled. Witten has shown how the small unified coupling of the standard model can be explained in terms of a product of a large number of factors of order one in a geometry of large dimensions. We will assume that similar numerical factors explain the strength of the gauge interactions that lead to SUSY breaking.

The main role of the gauge interactions is not to break SUSY, but rather the discrete R symmetry. If we fix the moduli and treat the gauge theory as a flat space quantum field theory, then SUSY remains unbroken even though a nonperturbative superpotential is generated. The scale of this superpotential is determined via a standard renormalization group analysis in terms of the bare gauge coupling function $f(\phi/m_P, \chi/M)$, where we have indicated dependence on both bulk and boundary moduli. For simplicity we assume that f is a large constant f_0 plus a smaller, moduli dependent, term. The conclusions are not affected by this assumption. The scale μ of the nonperturbative superpotential is then determined by f_0. It takes the form

$$W_1 = \mu^3 w_1(\phi/m_P, \chi/M) \tag{1.8}$$

We have eliminated all (composite) superfields related to the gauge interactions from this expression by solving their F and D flatness conditions for fixed values of the moduli. The possibility of doing this is equivalent to the statement that the gauge theory does not itself break SUSY. We assume that W_1 does not vanish at any minimum of the effective potential. This is the statement of spontaneous R symmetry breaking. As a consequence, SUSY minima of the potential have negative cosmological constant of order at least μ^6/m_P^2 and are not attractors of the cosmological equations. Thus, cosmologically, R symmetry breaking forces the moduli to choose a minimum with spontaneously broken SUSY[2].

Phenomenology requires a value of μ which gives acceptable squark masses. The details depend on whether or not we can set the F terms of the boundary moduli equal to zero (if there are no bulk moduli this is not consistent with our other assumptions). If we can, then the nonvanishing F terms are of order $\frac{\mu^3}{m_P}$. A standard argument shows that squark masses will be of order $\frac{\mu^3}{m_P^2}$, about the same as the gravitino. Assuming this

[2]The tunneling amplitudes of such nonsupersymmetric vacua into supersymmetric AdS vacua are incredibly tiny and might be identically zero, as discussed in [2].

is about a TeV we find $\mu \sim 10^{13}$ GeV . An attractive feature of this scenario is that the positive and negative terms in the SUGRA potential are naturally of the same order of magnitude. Although we have no real understanding of why the cosmological constant is so small, this fact of nature is an indication of a relation between the scales of R symmetry breaking and of SUSY breaking. In models in which the SUSY breaking F term originates as a bulk modulus the correct order of magnitude relation between these scales arises automatically.

By contrast, if we assume that the SUSY breaking F term is that of a boundary modulus, the negative term in the potential is of order $\frac{M^2}{m_P^2} \sim 10^{-4}$ smaller than the positive term. To understand the cancellation of the cosmological constant, one can , following [2] introduce two gauge groups. The first leads to spontaneous R symmetry breaking with unbroken SUSY at a scale μ_1 while the second breaks SUSY at μ_2. If $(\mu_1/\mu_2)^6 \sim m_P^2/M^2$ one can again obtain "order of magnitude cancellation" of the cosmological constant, but the scenario clearly lacks simplicity. In this scenario squark masses are of order μ_2^3/M^2, and the gravitino is lighter than this by a factor $\sim 10^{-4}$ and weighs about $100 MeV$. μ_2 has to be about 5×10^{11} GeV.

The first of these scenarios is clearly simpler, but as we now recall, it leads to the cosmological moduli problem. The scalar fields in the bulk moduli multiplets acquire masses from the SUSY violating potential of order $m_M \sim \mu^3/m_P^2$ which is the same order of magnitude as the gravitino and squark masses, *i.e.* a TeV. They have only nonrenormalizable couplings to ordinary matter, scaled by m_P. Thus, their nominal reheat temperature , $\sqrt{m_M^3/m_P}$ is of order $\sim 3 \times 10^{-2}$ MeV, and the universe is matter dominated at the time that nucleosynthesis is supposed to be taking place. The thermal inflation scenario [12] can solve this problem, and we will review another solution [5] below, but it might tempt us into adopting the scenario with boundary moduli as the instigators of SUSY breaking.

In this case, one would assume that all bulk moduli are frozen by the initial superpotential of order M^3. Dine [3] has advocated that the proper vacuum should be an enhanced symmetry point of moduli space at which all moduli (he does not make a distinction between bulk and boundary fields) are nonsinglets. We temporarily adopt this point of view, but only for the bulk moduli. Then the boundary moduli masses are of order 1 TeV, but their couplings to ordinary matter are scaled by M rather than m_P. The reheat temperature is rescaled by a factor of 10^2 and is (just) above the temperature for nucleosynthesis. The Hot Big Bang occurs just in time to light the furnace in which the primordial elements were formed.

One still has to account for baryogenesis. Adopting a mechanism suggested long ago by Holman, Ramond and Ross [15] we aver that this can come from the decay of the moduli themselves. All of their interactions are of order the fundamental scale of M theory, so there is no reason for them to preserve accidental symmetries like baryon and lepton number. It is quite reasonable that they also violate CP, though the status of CP in M theory is somewhat more obscure. The decay itself is an out of equilibrium process, so all of the Sakharov criteria for baryogenesis are fulfilled. However, we must also take note of the theorem of Weinberg [16], according to which baryon number violating terms in the Hamiltonian must act twice in order to generate an asymmetry. In the decay of moduli, the first action of the Hamiltonian comes at no cost in amplitude, because the modulus must decay somehow and there is no reason for its baryon number violating decays to be significantly smaller than those which conserve baryon number. However the second baryon number violating interaction should not be highly suppressed if we want to generate a reasonable baryon asymmetry. Indeed, a one TeV, gravitationally coupled, particle which produces a baryon asymmetry of order one in its decay, also produces of order (1TeV/3MeV) or $\sim 3 \times 10^5$ photons. Thus a large suppression of the average baryon number per decay would give too small a baryon asymmetry. A way out of this difficulty is to admit renormalizable baryon number violating operators in the supersymmetric standard model. Discrete symmetries such as a Z_2 lepton parity [13] can adequately suppress all unobserved baryon and lepton number violating processes in the laboratory, while allowing such operators with quite large coefficients. An unfortunate casualty of this mechanism is the lightest SUSY particle. The LSP is no longer stable in the scenario described above and we have to look elsewhere for a dark matter candidate.

With this scenario in mind, let us return to the situation with bulk moduli. Suppose that the coefficient in the order of magnitude relation between the moduli mass and the fundamental parameters is $m_M = 5 \times \mu^3/m_P^2$, while the squark mass is actually $m_{\tilde{q}} = \mu^3/4m_P^2 = 1$ TeV. Then the reheat temperature for the bulk moduli is multiplied by a factor of $20^{3/2} \sim 10^2$ and is again just above 1 MeV. Nucleosynthesis is again saved and baryogenesis can take place in the process of reheating. Again we must invoke renormalizable baryon number violation. Now however, there are natural candidates for dark matter. Imagine a boundary modulus whose potential energy is substantially smaller than the the estimate μ^3/M^2 coming from 1.8. We will call this the dark modulus, because it will be our dark matter candidate. It has a potential of the form $U = \Lambda^4 u(D/M)$. (In [5], where this scenario was first proposed, the candidate was a QCD axion field (which arises under certain natural conditions in Horava-Witten scenarios[24]). This model works, but the mechanism is much more general and does not require energy densities as small as those of the axion.

Now, briefly review cosmic history. First we have inflation generated by bulk moduli fields which are not on the true moduli space[3] . This period ends after of order 100 e-foldings, and the universe is heated by inflamoduli decay to a temperature of order 10^9 GeV . The primordial plasma quickly redshifts away. Furthermore, as soon as the inflamoduli potential energy density falls to μ^6/m_P^2, the universe becomes dominated by

[3]Perhaps we should call these *inflamoduli*.

the coherent oscillations of the true bulk moduli. The dark modulus remains frozen at some generic point on its potential until the Hubble parameter falls to the mass scale of this field. At this point the energy density of the universe is of order $\rho \sim m_P^2 \Lambda^4 / M^2$ which is of order $(m_P/M)^2 \sim 10^4$ times larger than the energy density of the dark modulus. The important point now is that this ratio is preserved by further cosmic evolution until the true bulk moduli decay. After that time, the dark energy density grows linearly with the inverse temperature relative to radiation, and matter radiation equality occurs at $10^{-4} MeV$. This is close enough to the true value for the observable universe that the factors of order one which we have neglected throughout might account for the difference. Λ must satisfy two constraints in order for this scenario to work: the dark moduli must remain frozen until the true bulk moduli begin to oscillate, and the dark modulus must have a lifetime at least as long as the age of the universe. The second constraint is by far the stronger, and leads to $\Lambda < 3 \times 10^6$ GeV. Axions satisfy this constraint by a large margin. Note that this scenario completely removes the conventional cosmological constraint on the axion decay constant. Axions will be very weakly coupled and will escape all of the usual schemes for detecting them.

In view of the more natural explanation of the ratio between R symmetry and SUSY breaking scales, and the existence of a dark matter candidate in the bulk modulus scenario for SUSY breaking, we tentatively reject the idea that SUSY breaking is triggered by the F term of a boundary modulus. Its only advantage over the bulk modulus scenario is that we do not have to massage coefficients of order one in order to push the reheat temperature above an MeV.

For completeness, we should also discuss the possibility that SUSY breaking itself is caused by gauge interactions which are weakly coupled at the fundamental scale. This is required if we assume, with Dine [3][21][20], that moduli are fixed at some enhanced symmetry point. Scenarios of this sort are attractive because they allow us to use the idea of gauge mediation [6] to solve the SUSY flavor problem. Gauge interactions generate superpotentials of the form $\mu_1^3 w_{g_1}(C_1/m_1) + \mu_2^3 w_{g_2}(C_2/m_2)$, where the $C's$ are composite superfields and the m_i the nonperturbative low energy scales generated by asymptotic freedom. Again, in order to cancel the cosmological constant, we must introduce an R breaking gauge theory with scale (m_1), which preserves SUSY and a SUSY breaking gauge theory, with scale related by $m_1^6 = m_P^2 m_2^4$.

There is no cosmological moduli problem in this picture, since all moduli are assumed to be frozen by the initial superpotential. Moduli and dark matter in gauge mediated SUSY breaking models have been discussed in [25].

1.2. Density Fluctuations Redux

There is a small discrepancy in what we have said up till now, which reader may have been rushed into ignoring. We bragged about achieving the right magnitude for energy density fluctuations of the inflaton, but then proceeded to claim that the energy we see today in the universe comes from another source entirely, *viz.* the true bulk moduli.

It is easy to see however that the true moduli inherit the fluctuations of the inflaton. In a given region the moduli fields start to oscillate when the Hubble constant is about equal to their mass. In a region of inflaton overdensity, this will happen later and the ratio of modular energy density in the overdense and average regions will start to increase like a^3. This will continue until the moduli in the overdense region begin to oscillate, a fter which the ratio will remain constant. Since the decrease of oscillating modular energy and oscillating inflaton energy follows the same scaling law, the magnitude of modular fluctuations will be the same as those in the original inflaton field.

We have assumed here that the true moduli begin to oscillate before the inflatons decay into radiation. Since the reheat temperature is 10^9 GeV and the oscillation energy scale is 10^{11} GeV, this assumption is valid.

Another question to worry about is the possibility of large isocurvature fluctuations in the true bulk moduli fields. However, during inflation, when the inflamoduli are excited away from their minimum, these are not light fields. The nonzero values of the inflamoduli break R symmetry. The true moduli space is a "river valley" running between the hills of the inflationary potential, and during inflation the system lies in the hills above the valley, where the potential is not flat in the valley direction. Indeed, this situation persists long into the era when the inflamoduli have begun to oscillate, because of the factor of 10^{20} between the inflationary and SUSY violating energy densities.

These issues deserve a more careful analysis, because it is possible that the transfer of fluctuations could leave some observable relic in the cosmic microwave background or that an observable level of isocurvature fluctuations could be generated. It is unclear to me whether reliable conclusions can be obtained without more information about the nature of the potential. Nonetheless, it appears that to a first approximation, the true moduli inherit the adiabatic perturbations of the inflaton field, so that the estimates we made above can be directly related to measurements of microwave background fluctuations.

1.3. Generalizing Horava-Witten

The moduli space of 11 dimensional SUGRA compactifications which preserve $\mathcal{N} = 1$ SUSY in four Minkowski dimensions splits into three components. These are Joyce sevenfolds, F theory limits of compactification on Calabi-Yau fourfolds, and Heterotic limits of compactification on $K3 \times CY_3$. These may be continously connected when short distance physics is properly taken into account. In addition, there may be many branches of moduli space which join onto these through generalized extremal transitions. The moduli space is thus highly complex.

The cosmological arguments of this paper indicate that the phenomenologically relevant compactifications may belong to a highly constrained submanifold of this complicated space. Namely, they should preserve eight supercharges in the bulk. The breaking to $\mathcal{N}=1$ should occur only on branes. SUGRA compactifications preserving eight SUSYs are much more constrained. The holonomy must be contained in $SU(3)$ which implies that the manifold is the product of a Calabi-Yau threefold times a torus, modded out by a discrete group Γ. In order to obtain a smooth manifold with eight SUSYs , Γ should act freely and the holonomy around the new cycles created by Γ identification should be in $SU(3)$. Clearly, a way to obtain Horava-Witten like scenarios is to allow fixed manifolds of Γ, on which an additional SUSY is broken. The original scenario of Horava and Witten was a $CY_3 \times S^1$ compactification in which Γ is a Z_2 reflection on the S^1. The fixed planes carry $E8$ gauge groups, and one must also choose an appropriate gauge bundle. A further generalization allows five branes wrapped on two cycles of CY_3 to live between the planes.

It seems likely that more complicated choices of Γ might lead to a wider class of scenarios. The problem of classifying scenarios of this type seems quite manageable [4]. The moduli space of compactifications of M theory on CY_3 times a torus has a reasonably complicated structure, replete with extremal transitions. Nonetheless, it is considerably simpler than the fourfold or Joyce manifold problem, and we know much more about its structure. Thus, if cosmology really points us in the direction of generalized Horava-Witten compactifications, we have made real progress in the search for the true vacuum of M theory.

2. Conclusions

Witten's explanation of the discrepancy between the Planck and unification scales in the context of Horava-Witten compactifications, poses a challenge for inflationary cosmology and particularly for the notion that moduli are inflatons. In fact, the enhanced bulk SUSY of these compactifications gives us a clean definition of modular inflatons. The scenario then makes an order of magnitude prediction of the amplitude of primordial density fluctuations in terms of the unification scale.

Cosmological arguments first discussed in [2] then focus attention on the true moduli space of M theory, a locus of enhanced discrete R symmetry. Such a space almost certainly exists [8]. It is the attractor of postinflationary cosmological evolution. The further evolution of the universe then depends on whether this space contains bulk moduli. In the attractive scenario in which it does, the initial Hot Big Bang generated by inflation, is soon dominated by the energy density stored in coherent oscillations of true bulk moduli. By making optimistic but plausible assumptions about coefficients of order one in order of

[4]Preliminary results on the classification problem have been obtained by L.Motl.

magnitude estimates, one obtains a reheat temperature above that required by nucleosynthesis. The decay of true bulk moduli, rather than that of the inflaton, generates the Hot Big Bang of classical cosmology. The baryon asymmetry must also be generated in these decays, and this is possible if the SUSY standard model contains renormalizable baryon number violating interactions (compatible with laboratory tests of baryon and lepton number conservation). As a consequence of this, there is no LSP dark matter candidate. Instead, boundary moduli with a suppressed potential energy act as a natural source of dark matter. Indeed, the ratio between the Planck and unification scales appears again in this scenario, this time in explaining the temperature at which matter and radiation make equal contributions to the energy density of the Universe. This estimate comes out an order of magnitude too high, but given the crudity of the calculation it seems quite plausible that this mechanism could be compatible with observation. The "dark modulus "which appears in this scenario could be a QCD axion with decay constant of order the unification scale. Our unconventional origin for the Hot Big Bang completely removes the cosmological upper bound on this decay constant. Such a particle would be undetectable in presently proposed axion searches.

If a cosmology like that outlined here turns out to be correct, one might be tempted to revise Einstein's famous estimate of the moral qualities of a hypothetical Creator. The current standard model of cosmology was constructed in the sixties. Since then there has been much speculation about cosmology at times earlier than that at which the primordial elements were synthesized. Most of it has been based on an eminently reasonable extrapolation of the Hot Big Bang to energy densities orders of magnitude higher. If the present scenario is correct, no such extrapolation is possible, and the conditions in the Universe in the first fraction of the First Three Minutes were considerably different from those at any subsequent time. There was a prior Big Bang after inflation, whose remnants may be forever hidden from us. The dark matter which dominates our universe is so weakly coupled to ordinary matter that its detection is far beyond the reach of currently planned experiments. The QCD and electroweak phase transitions never occurred.

The only dramatic prediction of this scenario for currently planned experiments is the occurrence of renormalizable baryon number violation in the low energy SUSY world. The details of the baryogenesis scenario envisaged here should be worked out more carefully, and combined with laboratory constraints, to nail down precisely which kind of operators are allowed. The scenario is thus easily falsifiable, but even the discovery of renormalizable baryon number violating interactions among SUSY particles will not be a confirmation of our cosmology. Similarly, any evidence for the existence of more or less conventional WIMP dark matter will be a strong indication that the present speculations are incorrect, but the failure to discover WIMPS will not prove that they are correct.

Instead one will have to rely on the slow accumulation of evidence against alternatives:

ruling out vanishing up quark mass and spontaneous CP violation as solutions to the strong CP problem, the failure of conventional axion and WIMP searches, the discovery of renormalizable B violation. These will be steps on the road to proving that this cosmology is correct, but the end of that road is not in sight.

Acknowledgments

I am grateful to Sean Carroll, Willy Fischler, Lubos Motl and Paul Steinhardt for valuable discussions. This work was supported in part by the DOE under grant number DE-FG02-96ER40559.

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